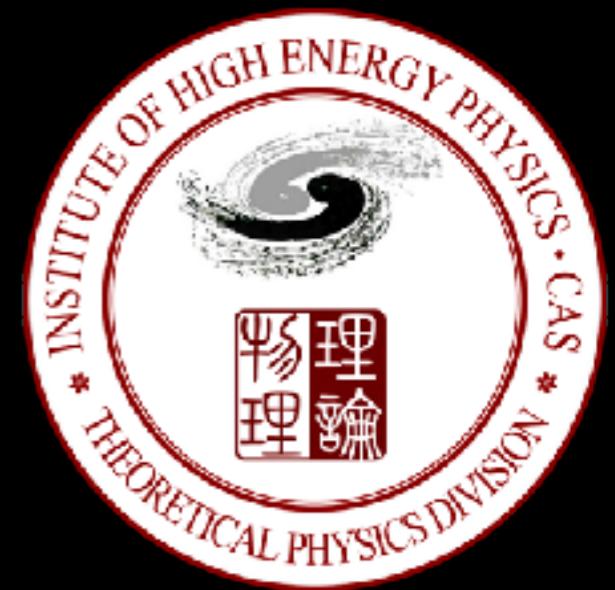
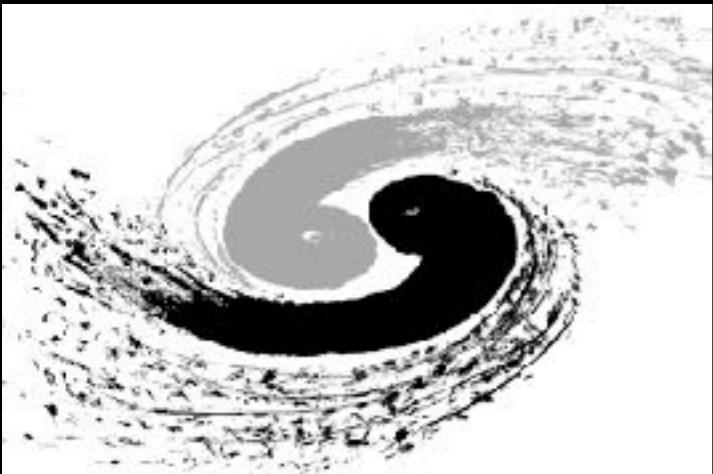


# Precise predictions at colliders

Zhao Li  
IHEP-CAS

CLHCP2016, PKU  
2016.12.16





LIVE SCIENCE  
[www.livescience.com](http://www.livescience.com)

# What is a Higgs Boson?

The elusive Higgs boson, if found, would complete the Standard Model of physics. It is thought that matter obtains mass by interacting with the Higgs field. If Higgs did not exist, according to the model, everything in the universe would be massless.

The "cocktail party" analogy

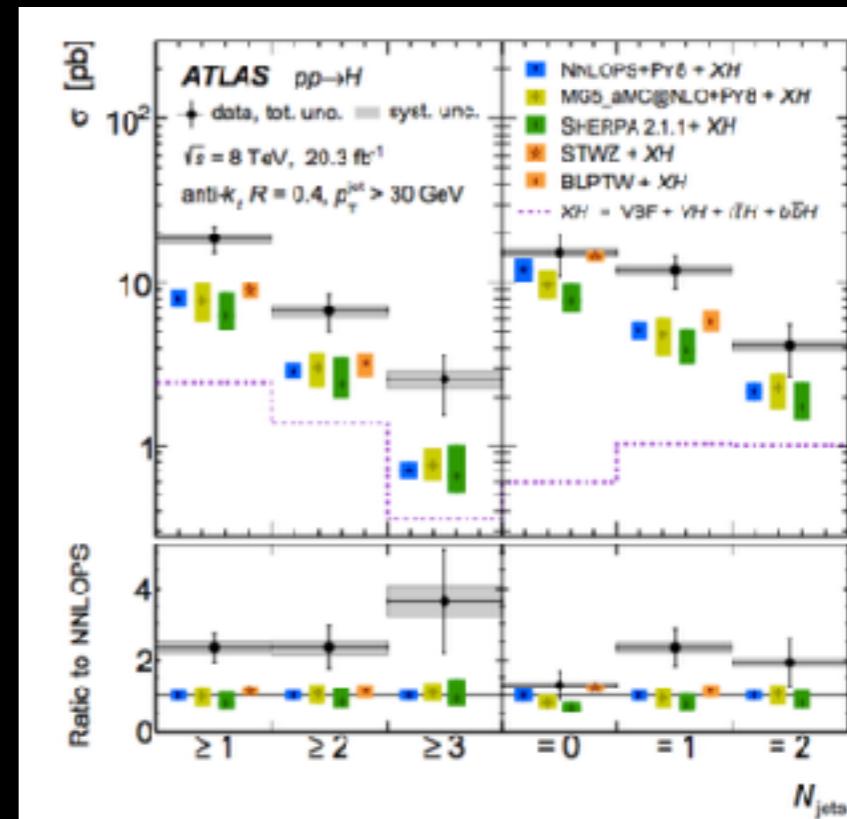
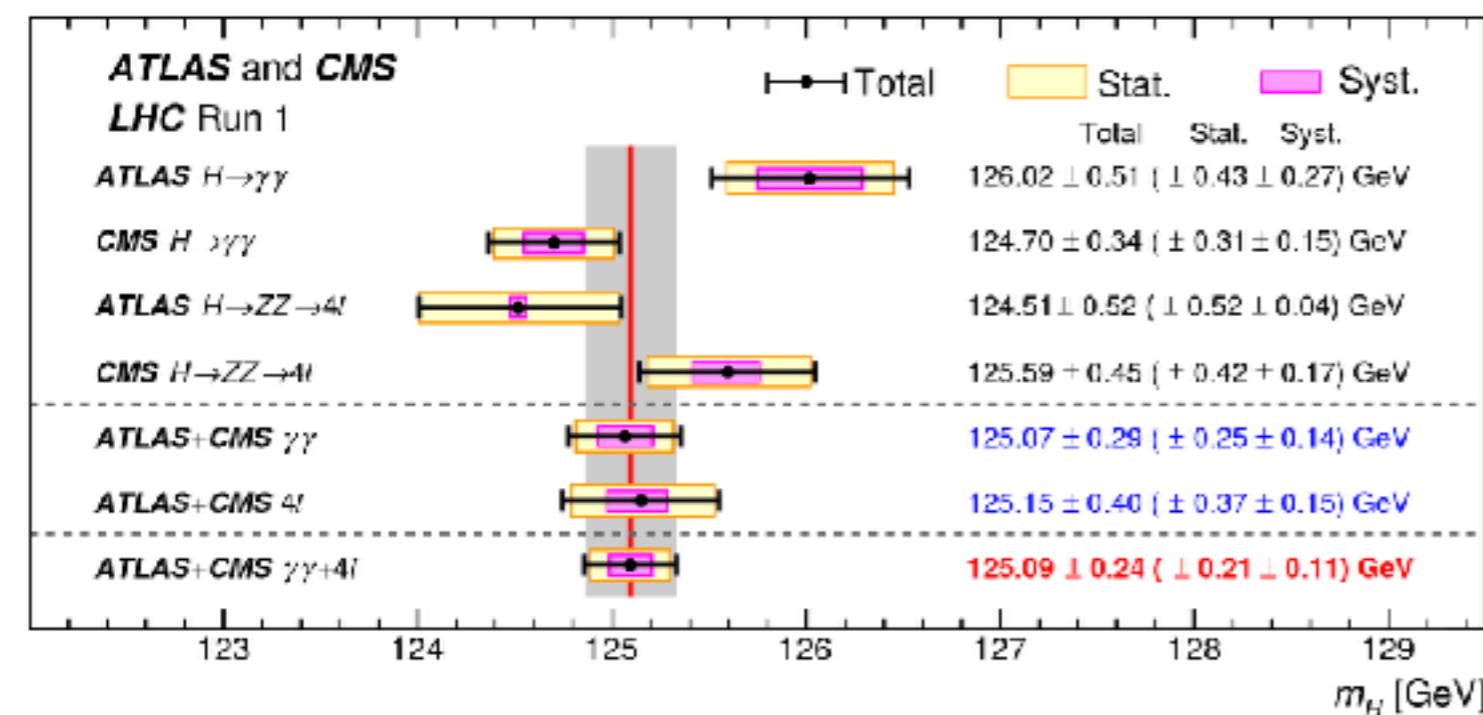
The diagram illustrates the 'cocktail party' analogy. On the left, a room full of people (grey circles) represents the Higgs field. A single person with a crown (a celebrity) enters the room. On the right, the people are clustered around the crowned individual, representing the Higgs boson interacting with matter. An arrow points from the text to this illustration.

Imagine a party where guests are evenly spaced around the room. The room of guests represents the Higgs field, which is everywhere in the universe. Suddenly a celebrity enters. Guests notice the celebrity and rush in closer to be near her, forming a tight knot.

SO. AMER. / GETTY IMAGES

KARL TATE / © LiveScience.com





$$V(\Phi) = \frac{\lambda}{4} \left( \Phi^\dagger \Phi \right)^2 - \mu^2 \Phi^\dagger \Phi$$

**SM**

$$\lambda_{HHH} = 3M_H^2/M_Z^2$$



**MSSM (2HDM)**

$$\begin{aligned} \lambda_{hhh} &= 3 \cos 2\alpha \sin(\beta + \alpha) + 3 \frac{\epsilon}{M_Z^2} \frac{\cos \alpha}{\sin \beta} \cos^2 \alpha \\ \epsilon &= 3G_F M_t^4 / (\sqrt{2} \pi^2 \sin^2 \beta) \end{aligned}$$



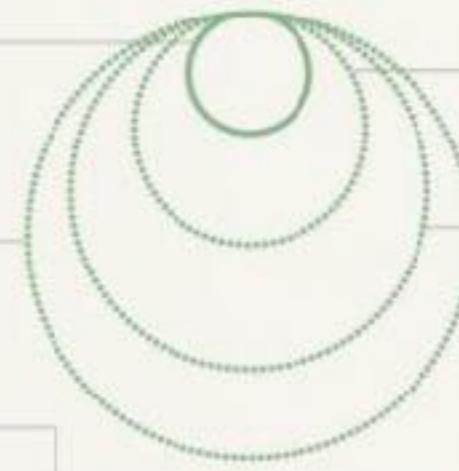
## COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.

CERN's Large Hadron Collider  
Circumference: 27 km  
Energy: 14 TeV

US/European super proton collider  
100 km; 100 TeV

International Linear Collider  
Length: 31 km  
 $\leq 1$  TeV



China's electron-positron collider  
52 km; 240 GeV

China's super proton collider  
52 km;  $\leq 70$  TeV

China-hosted international electron-positron collider  
80 km; 240 GeV

China-hosted international super proton collider  
80 km;  $\leq 100$  TeV

— Existing ----- Proposed  
TeV, teraelectronvolt; GeV, gigaelectronvolt



High Precision!

# Virtual (Loop) correction

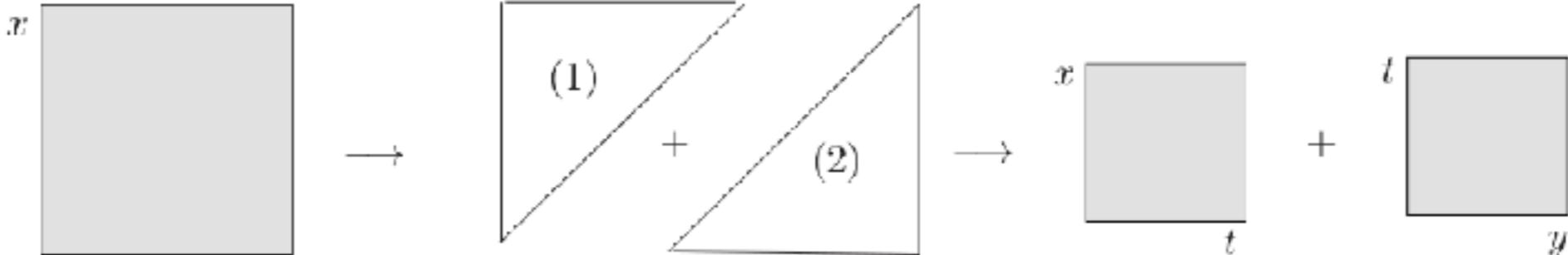
- **Analytical Approach**

*Simple processes only, i.e. not too many scales. No breakthrough after more than ten years struggle.*

- **Numerical Approach**

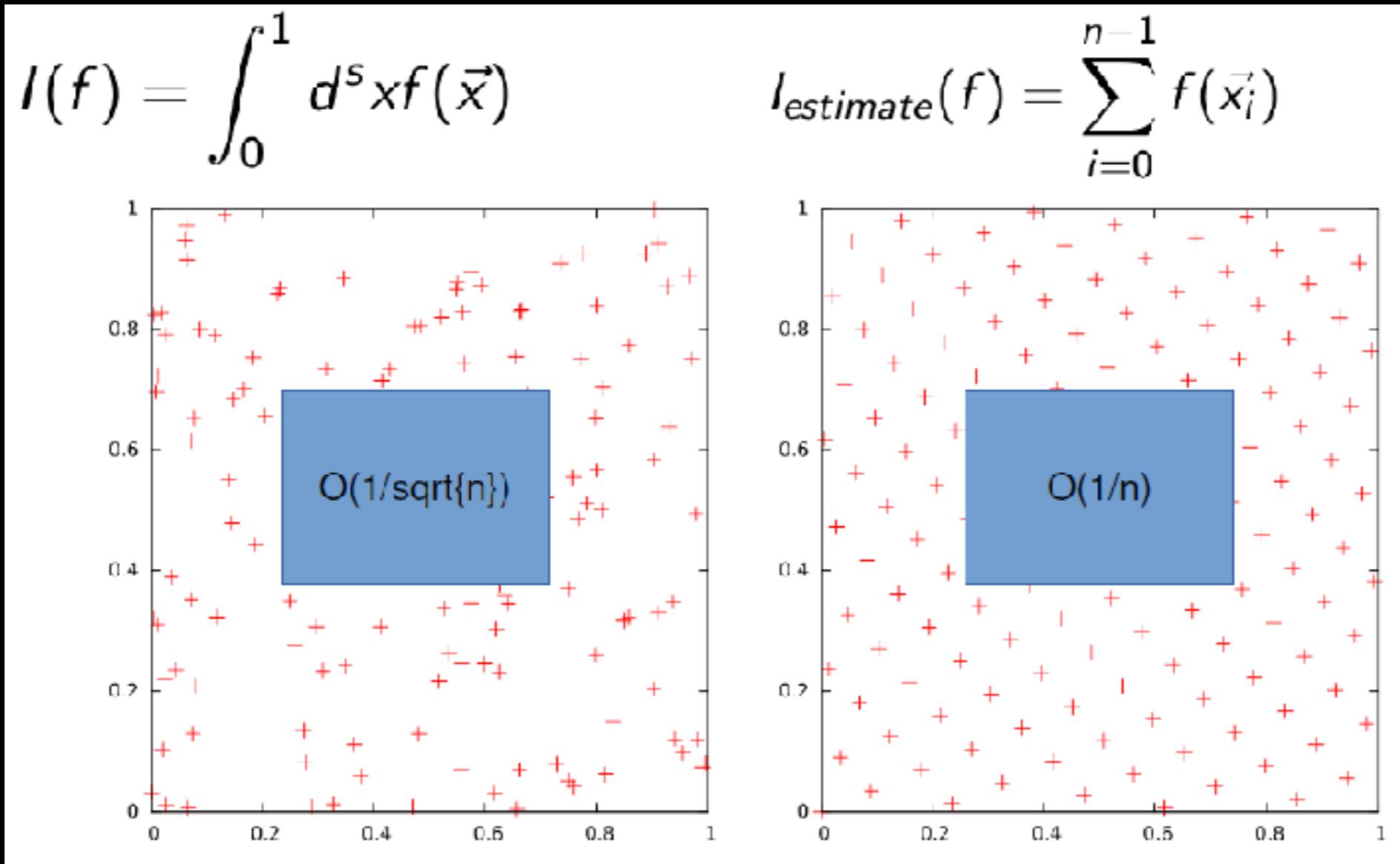
*Conventionally too slow. Popular algorithms are “Sector Decomposition” and “Mellin-Barnes”*

# Sector Decomposition

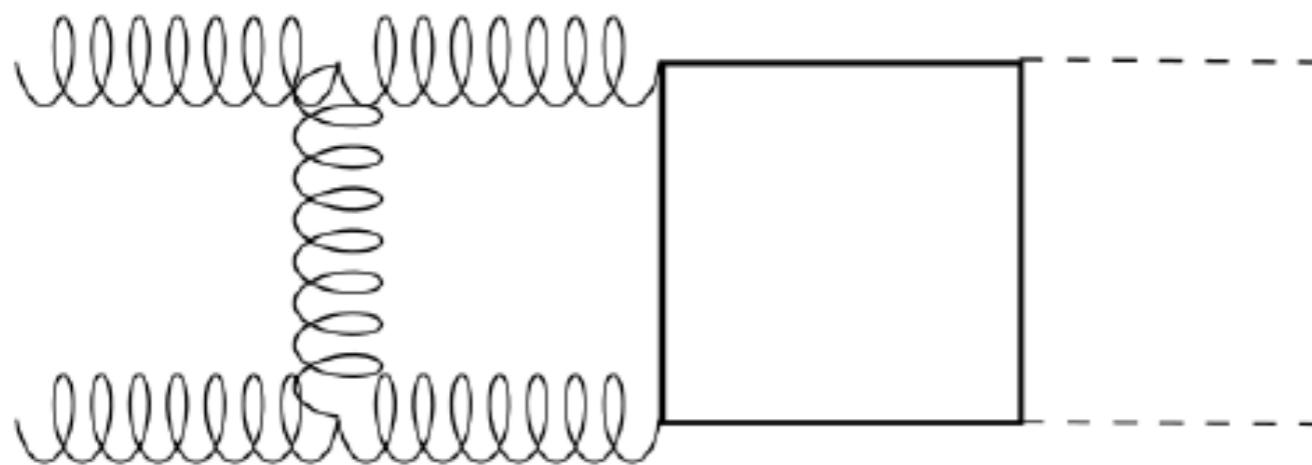
$$I = \int_0^1 dx \int_0^1 dy \ x^{-1-\epsilon} y^{-\epsilon} (x + (1-x)y)^{-1}$$

$$I = \int_0^1 dx \ x^{-1-\epsilon} \int_0^1 dt \ t^{-\epsilon} (1 + (1-x)t)^{-1}$$
$$+ \int_0^1 dy \ y^{-1-2\epsilon} \int_0^1 dt \ t^{-1-\epsilon} (1 + (1-y)t)^{-1}$$

Very General, but conventionally slow.

# Quasi-Monte-Carlo & GPU

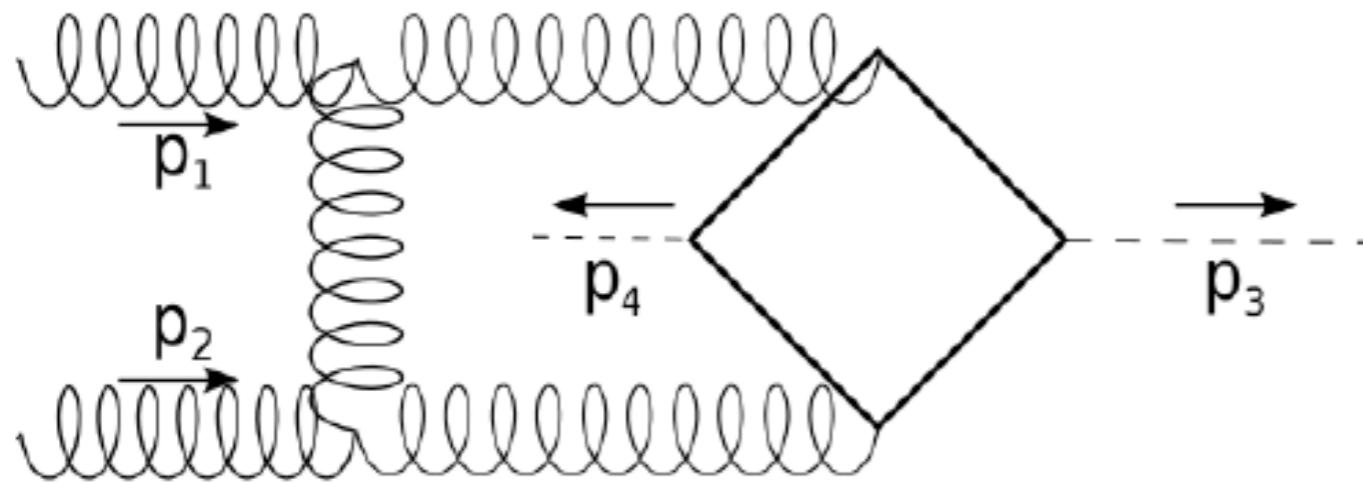


Z.Li, J.Wang, Q.Yan and X.Zhao  
Chinese Physics C, Vol. 40, No. 3 (2016) 033103



$$I_C = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=2} \frac{P_i}{\epsilon^i}.$$

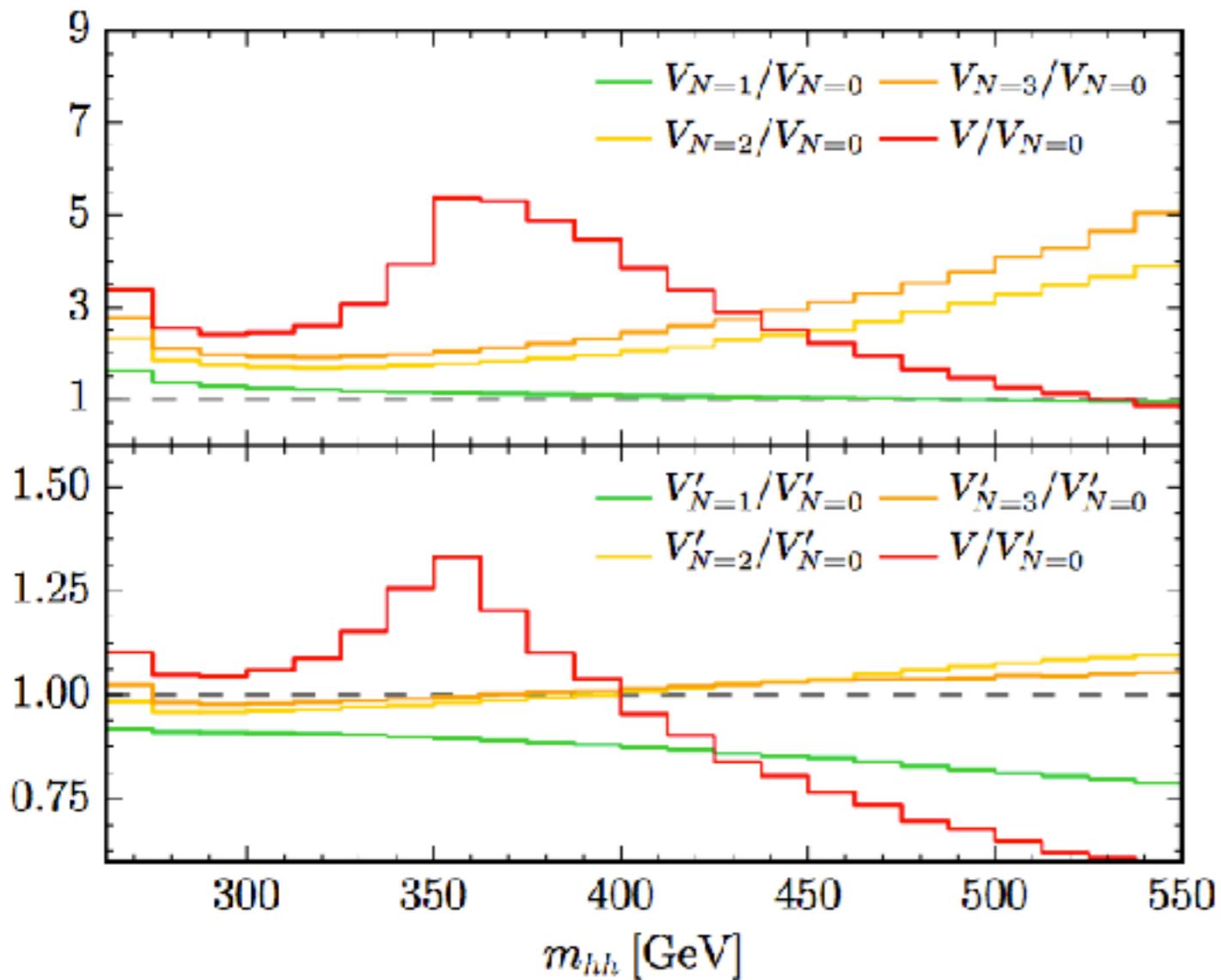
	Vegas/CPU	QMC/GPU
$P_2$	$-7.959 \pm 0.009 - 10.586i \pm 0.009i$	$-7.949 \pm 0.003 - 10.585i \pm 0.005i$
$P_1$	$3.9 \pm 0.1 - 28.1i \pm 0.1i$	$3.831 \pm 0.005 - 28.022i \pm 0.005i$
$P_0$	$-3.9 \pm 0.8 + 92.3i \pm 0.8i$	$-4.63 \pm 0.07 + 92.13i \pm 0.07i$
Integration Time	45540s	19s



$$I_D = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=2} \frac{P_i}{\epsilon^i}.$$

	Vegas/CPU	QMC/GPU
$P_2$	$-3.848 \pm 0.004 + 0.0005i \pm 0.003i$	$-3.8482 \pm 0.0007 + 0.0004i \pm 0.0003i$
$P_1$	$3.81 \pm 0.03 - 6.41i \pm 0.03i$	$3.83 \pm 0.02 - 6.40i \pm 0.02i$
$P_0$	$77.2 \pm 0.2 + 20.1i \pm 0.2i$	$77.2 \pm 0.1 + 19.9i \pm 0.1i$
Integration Time	54290s	20s

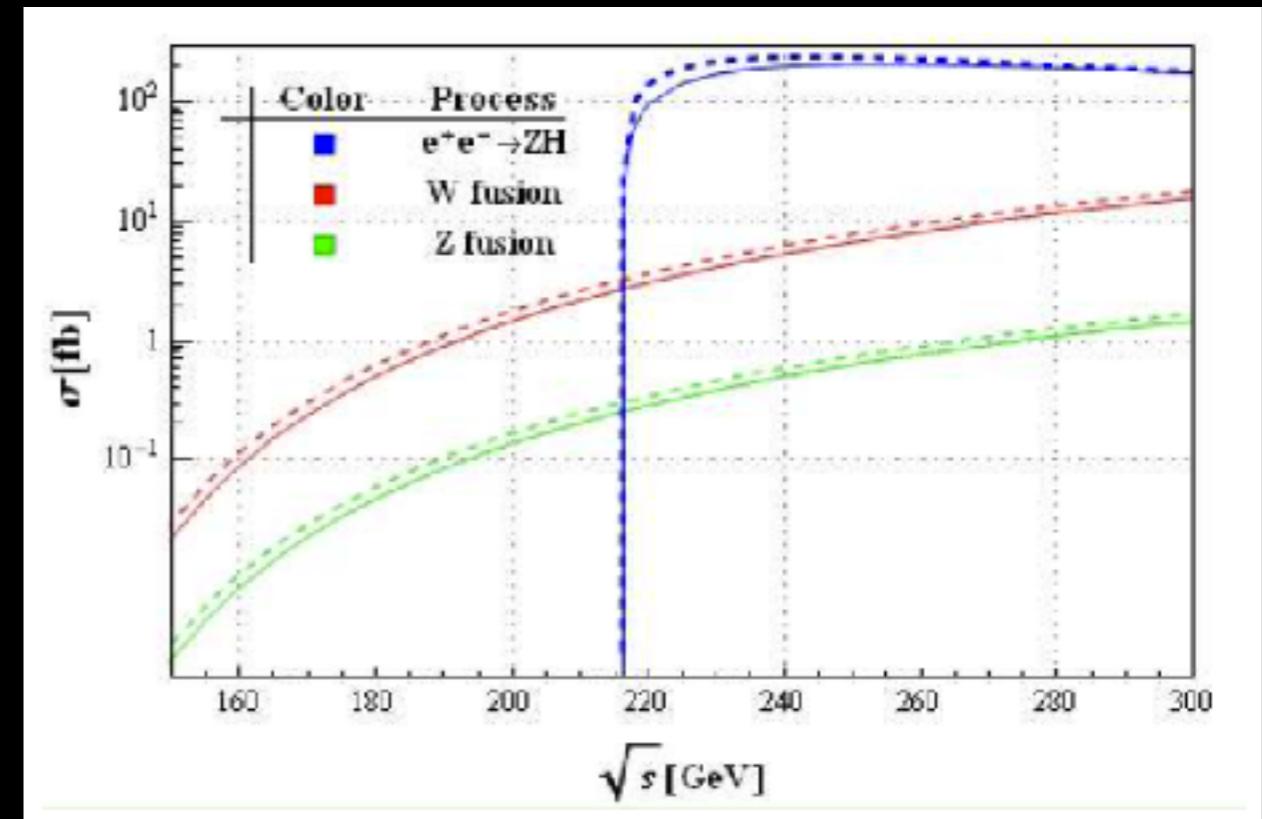
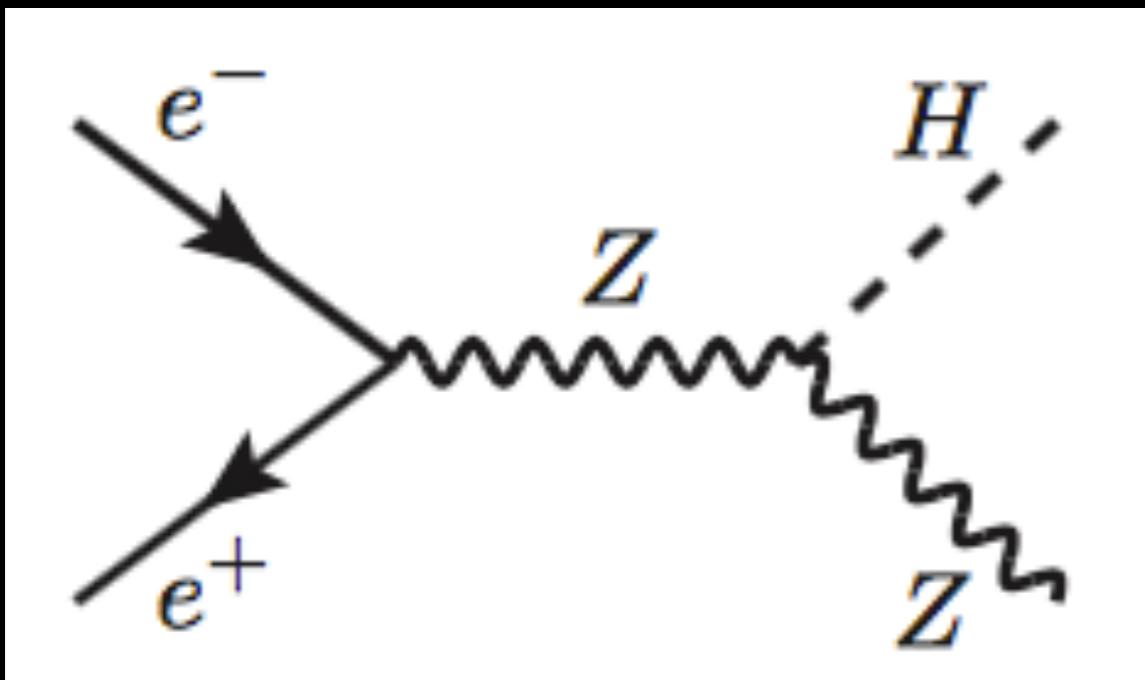
# Applied to Higgs pair production @ LHC



S.Borowka, N.Greiner, G.Heinrich,  
S.P. Jones, M.Kerner, J.Schlenk,  
U.Schubert, T.Zirke  
Phys.Rev.Lett. 117 (2016) no.1,  
012001

FIG. 2. Comparison of the virtual amplitude with full top-quark mass dependence to various orders in a  $1/m_t^2$  expansion.  $V'_N$  denotes the Born-improved HEFT result to order  $N$  in the  $1/m_t^2$  expansion, i.e.  $V'_N = V_N B/B_N$ .

# CEPC as Higgs factory



One million Higgs bosons!

# Mixed QCD-EW corrections for Higgs boson production at e+e- colliders

**Y.Gong, Z.Li, X.Xu, L.Yang and X.Zhao**  
**arXiv:1609.03955[hep-ph]**

**Q.Sun, F.Feng, Y.Jia, W. Sang**  
**arXiv:1609.03995[hep-ph]**

# Mixed QCD-EW corrections for Higgs boson production at e+e- colliders

1.3%

$\sqrt{s}$ (GeV)	$\sigma_{\text{LO}}$ (fb)	$\sigma_{\text{NLO}}$ (fb)	$\sigma_{\text{NNLO}}$ (fb)	$\sigma_{\text{NNLO}}^{\text{exp.}}$ (fb)
240	256.3(9)	228.0(1)	230.9(4)	230.9(4)
250	256.3(9)	227.3(1)	230.2(4)	230.2(4)
300	193.4(7)	170.2(1)	172.4(3)	172.4(3)
350	138.2(5)	122.1(1)	123.9(2)	123.6(2)
500	61.38(22)	53.86(2)	54.24(7)	54.64(10)

TABLE I. The NNLO predictions for the total cross sections at various collider energies.

Y.Gong, Z.Li, X.Xu, L.Yang and X.Zhao  
arXiv:1609.03955[hep-ph]

# Mixed QCD-EW corrections for Higgs boson production at e+e- colliders

$\sqrt{s}$ (GeV)	$\mathcal{O}(m_t^2)$	$\mathcal{O}(m_t^0)$	$\mathcal{O}(m_t^{-2})$	$\mathcal{O}(m_t^{-4})$
240	81.8%	16.2%	1.4%	0.4%
250	81.7%	16.1%	1.5%	0.5%
300	80.0%	15.2%	2.1%	1.1%
350	69.7%	12.6%	2.7%	2.1%
500	137%	18.6%	17.3%	31.1%

TABLE II. Convergence of the  $1/m_t^2$  expansion for the mixed QCD-EW corrections.

Y.Gong, Z.Li, X.Xu, L.Yang and X.Zhao  
arXiv:1609.03955[hep-ph]

# Conclusion

- Precise prediction is key for LHC & CEPC-SPPC.
- Multi-loop with multi-scale can veto many conventional approaches.
- Numerical approach can be an practical & efficient choice before breakthrough.
- Many works are ahead...

Thank you!